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The baryon fraction in hydrodynamical simulations of galaxy clusters

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ABSTRACT

We study the baryon mass fraction in a set of hydrodynamical simulations of galaxy clusters performed using the Tree+SPH code GADGET-2. We investigate the dependence of the baryon fraction upon the radiative cooling, star formation, feedback through galactic winds, conduction and redshift. Both the cold stellar component and the hot X-ray emitting gas have narrow distributions that, at large cluster-centric distances $r \gtrsim R_{500}$, are nearly independent of the physics included in the simulations. Only the non-radiative runs reproduce the gas fraction inferred from observations of the inner regions ($r \approx R_{2500}$) of massive clusters. When cooling is turned on, the excess star formation is mitigated by the action of galactic winds, but yet not by the amount required by observational data. The baryon fraction within a fixed overdensity increases slightly with redshift, independent of the physical processes involved in the accumulation of baryons in the cluster potential well. In runs with cooling and feedback, the increase in baryons is associated with a larger stellar mass fraction that arises at high redshift as a consequence of more efficient gas cooling. For the same reason, the gas fraction appears less concentrated at higher redshift. We discuss the possible cosmological implications of our results and find that two assumptions generally adopted, (1) mean value of $Y_{\rm b} = \frac{f_{\rm b}}{\Omega_{\rm b}/\Omega_{\rm m}}$ not evolving with redshift, and (2) a fixed ratio between $f_{\rm star}$ and $f_{\rm gas}$ independent of radius and redshift, might not be valid. In the estimate of the cosmic matter density parameter, this implies some systematic effects of the order of $\Delta\Omega_{\rm m}/\Omega_{\rm m} \lesssim +0.15$ for non–radiative runs and $\Delta\Omega_{\rm m}/\Omega_{\rm m} \approx +0.05$ and $\lesssim -0.05$ for radiative simulations.

Key words: cosmology: miscellaneous – methods: numerical – galaxies: cluster: general – X-ray: galaxies.

1 INTRODUCTION

Baryons in galaxy clusters, mainly in the form of stars in galaxies and hot X-ray emitting plasma, trace the potential of the collapsed structure in which they fall into. At the same time, their spatial distribution and thermodynamical properties are affected by the physical processes acting on them. Measurement of direct cluster observables, such as stellar optical light and hot gas X-ray emission, is the only viable approach to investigate the physics that drives the evolution of such structures. The observed relations among proxies of the internal energy and entropy levels show that, at least in massive systems, the dominant baryonic component of the intra–cluster medium (ICM) has a luminosity, temperature and mass that well follow those predicted under the assumptions of a plasma emitting by bremsstrahlung and sitting in hydrostatic equilibrium with the underlying dark matter potential (e.g. Kaiser 1991, Evrard & Henry 1991).

Moreover, the fact that galaxy clusters are relatively well isolated structures, that form in correspondence of the highest peaks of the primordial gravitational fluctuations, suggests that their relative baryon budget and the mass function are highly sensitive tests of the geometry and matter content of the Universe. In particular, using X-ray observations of the baryonic content to infer the gas and total mass of relaxed clusters in hydrostatic equilibrium allows one to place a lower limit to the cluster baryon mass fraction, which is expected to match the cosmic value $\Omega_{\rm b}/\Omega_{\rm m}$ (White et al. 1993, Evrard 1997, Mohr, Mathiesen & Evrard 1999, Ettori & Fabian 1999, Roussel, Sadat & Blanchard 2000, Allen et al. 2002, Ettori et al. 2003, Ettori 2003, Allen et al. 2004).

The purpose of the present work is to use an extended set

of hydrodynamical simulations of galaxy clusters, treating a variety of physical processes, to study how the spatial distribution of the baryons, as contributed both by the stellar component and by the hot X-ray emitting gas, are affected by the physical conditions within clusters. In this respect, our analysis extends previous analyses of the baryon fraction in cluster simulations which included only non–radiative physics (Evrard 1990, Metzler & Evrard 1994, Navarro et al. 1995, Lubin et al. 1996, Eke et al. 1998, Frenk et al. 1999, Mohr et al. 1999, Bialek et al. 2001), and the processes of cooling and star formation (Muanwong et al. 2002, Kay et al. 2004, Ettori et al. 2004, Kravtsov et al. 2005).

The paper is organized as follows: in Section 2, we describe our dataset of simulated galaxy clusters; in Section 3, we present the results obtained from this set of simulations on the gas and baryon fraction, also comparing these results to the observational constraints. In Section 4 we compare our results to previous analyses based on different simulations. Finally, we summarize and discuss our findings in Section 5.

2 PROPERTIES OF THE SIMULATED CLUSTERS

We consider two sets of clusters, which have been selected from different parent cosmological boxes. The first set is extracted from the large–scale cosmological simulation presented in Borgani et al. (2004). The second one is a re-simulation of 9 galaxy clusters, extracted from a pre-existing lower–resolution DM–only simulation. Our simulations were carried out with GADGET-2 (Springel 2005), a new version of the parallel Tree+SPH simulation code GADGET (Springel et al. 2001). It includes an entropy-conserving formulation of SPH (Springel & Hernquist 2002), radiative cooling, heating by a UV background, and a treatment of star formation and feedback from galactic winds powered by supernova explosions (Springel & Hernquist 2003).

2.1 Clusters extracted from a cosmological Box

The first set of simulated clusters has been extracted from the large-scale cosmological simulation of a "concordance" ΛCDM model ($\Omega_{0m} = 0.3$, $\Omega_{0\Lambda} = 0.7$, $\Omega_{0b} = 0.019h^{-2}$, $h = 0.7$, $\sigma_8 = 0.8$; Borgani et al. 2004). Here we give only a short summary of its characteristics, and refer to that paper for more details. The run follows the evolution of 480^3 dark matter particles and an equal number of gas particles in a periodic cube of size $192h^{-1}$ Mpc. The mass of the gas particles is $m_{\rm gas} = 6.89 \times 10^8 h^{-1} M_\odot$, while the the Plummer-equivalent force softening is set to $7.5h^{-1}$ kpc from $z = 0$ to $z = 2$, while kept fixed in comoving units at higher redshift. At $z = 0$ we extract a set of 439 mass-selected clusters with virial masses $M_{\rm vir} > 5 \times 10^{13} h^{-1} M_\odot$.

The efficiency of conversion of the energy provided by SN explosions into a kinetic feedback (i.e. winds) is set to 50 per cent, which gives a wind speed of ≈340 km s^{-1}.

2.2 Resimulated clusters

This set includes simulations of 4 high mass systems with M_{200} =(1.1–1.8)$\times 10^{15} h^{-1} M_\odot$. The cluster regions were extracted from a dark-matter only simulation with a box-size of $479\, h^{-1}\,\mathrm{Mpc}$ of the same cosmological model as the first set, but with a higher normalization of the power spectrum, $\sigma_8 = 0.9$ (see Yoshida, Sheth & Diaferio 2001). Using the "Zoomed Initial Conditions" (ZIC) technique (Tormen 1997), they were re-simulated with higher mass and force resolution by populating their Lagrangian volumes in the initial domain with more particles, while appropriately adding additional high–frequency modes. The initial particle distributions (before displacement) are of glass type (White 1996). The mass resolution of the gas particles in these simulations $m_{\rm gas} = 1.7 \times 10^8\, h^{-1}\, M_\odot$. Thus, the clusters were resolved with between 2×10^6 and 4×10^6 particles, depending on their final mass. For all simulations, the gravitational softening length was kept fixed at $\epsilon = 30.0\, h^{-1}\,\mathrm{kpc}$ comoving (Plummer-equivalent), and was switched to a physical softening length of $\epsilon = 5.0\, h^{-1}\,\mathrm{kpc}$ at $z = 5$.

For simulations including star formation and feedback the SN efficiency in powering galactic winds is set to 50 per cent, as in the cosmological box, which turns into a wind speed of ≈340 km s^{-1}. For the sake of comparison, some runs have also been performed also by switched off the winds completely or increasing the SN efficiency to unity.

For some of the cluster simulations we also included the effect of heat conduction. Its implementation in SPH, which is both stable and manifestly conserves thermal energy even when individual and adaptive time–steps, has been described by Jubelgas, Springel & Dolag (2004). This implementation assumes an isotropic effective conductivity parameterized as a fixed fraction of the Spitzer rate, that we assume to be 1/3. It also accounts for saturation, which can become relevant in low-density gas. For more details on the properties of simulated galaxy clusters including thermal conduction see Dolag et al. (2004).

Furthermore, some simulations were carried out using a modified artificial viscosity scheme suggested by Morris & Monaghan (1997), where every particle evolves its own viscosity parameter. Whereas in this scheme shocks are as well captured as in the standard one, regions with no shocks do not suffer for a residual non–vanishing artificial viscosity. Therefore turbulence driven by fluid instabilities can be much better resolved and as a result of this, galaxy clusters simulated with this new scheme can build up sufficient level of turbulence–powered instabilities along the surfaces of the large scale velocity structure present in cosmological structure formation (Dolag et al. 2005).

In summary, this set of cluster was simulated 4 times, with different kind of physics processes included:

- *Gravitational heating only (code=G).*
- *Gravitational heating only with low viscosity scheme (code=GV)*: Like *G*, but using the alternative implementation of artificial viscosity. In this simulation, galaxy clusters are found to have up to 30 per cent of their thermal energy in the turbulent motion of the ICM, leading to a sizeable contribution of non–thermal pressure support in the center of galaxy clusters;
- *Cooling + Star Formation + Feedback with weak winds (code=FwW)*: the wind speed is fixed at ≈340 km s^{-1}.
- *Cooling + Star Formation + Feedback with weak winds and Conduction (code=FwWC)*: Conduction efficiency set to be $1/3$ of the Spitzer rate.

In order to have under control the effect of changing the feedback efficiency, one high–mass cluster was further simulated with the following setups:

- *Cooling + Star Formation + Feedback with no winds (code=F)*: Like *FwW*, but with winds switched off.
- *Cooling + Star Formation + Feedback with strong winds (code=FsW)*: Like *FwW*, but with wind speed increased to ≈480 km s^{-1}, corresponding to a SN efficiency of unity.

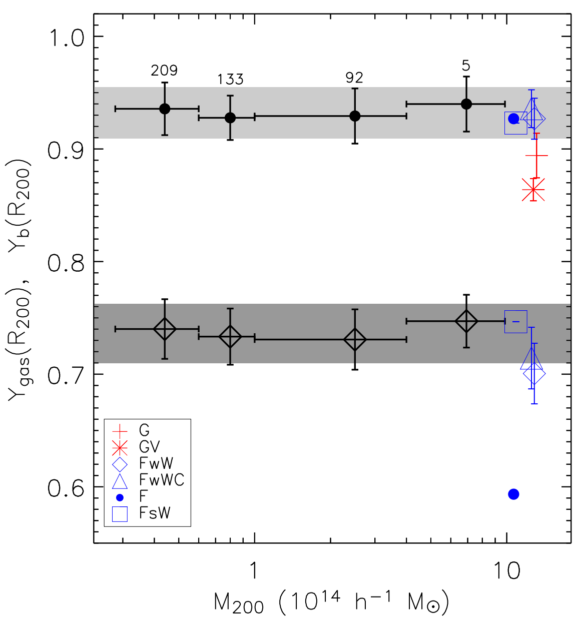

Figure 1. The baryon and gas mass fractions at R_{200} and $z = 0$ as functions of the virial mass. The solid dots with error-bars refer to the mean and dispersion measured in the corresponding bins in virial mass. The number of objects in each bin is indicated. The most massive re-simulated systems are also shown. The shaded regions indicate the 1σ range of $Y_{\rm gas}$ and $Y_{\rm b}$ for the set of simulated clusters extracted from the cosmological box.

The center of each cluster is defined as the position of the particle having the minimum value of the gravitational potential. Starting from this position, we run a spherical overdensity algorithm to find the radius R_{Δ_c} encompassing a given overdensity Δ_c, with respect to the critical one at the redshift under exam, and the mass M_{Δ_c} enclosed within this radius. In the present work, we consider values of the overdensity Δ_c equal to 2500, 500 and 200. The corresponding radii relate to the virial radius, which defines a sphere with virial overdensity (of ≈ 101 at $z = 0$ and ≈ 157 at $z = 1$ for our cosmological model and with respect to the critical value), as $(R_{2500}, R_{500}, R_{200}) \approx (0.2, 0.5, 0.7) \times R_{\rm vir}$. For each cluster, the hot gas mass fraction and the stellar mass fraction within a given radius r are then calculated as $f_{\rm gas}(<r) = M_{\rm gas}(<r)/M_{\rm tot}(<r)$ and $f_{\rm star}(<r) = M_{\rm star}(<r)/M_{\rm tot}(<r)$, respectively.

3 RESULTS FOR THE GAS AND STELLAR MASS FRACTIONS

For the sake of clarity, we define the quantities $Y_{\rm gas}$, $Y_{\rm star}$ and $Y_{\rm b}$ as the ratios between $f_{\rm gas}$, $f_{\rm star}$ and $f_{\rm b} = f_{\rm gas} + f_{\rm star}$, and the cosmic value adopted in the present simulations, $\Omega_{\rm b}/\Omega_{\rm m} = 0.13$. Their mean values (and standard deviations of the observed distributions, where available) at redshift $z = 0$, 0.3, 0.7 and 1 are quoted in Table 1 for the different physical conditions considered.

We compare in Fig. 1 the gas and baryon fraction as a function of the virial mass, for both the simulated clusters extracted from the cosmological box and for the subset of the re–simulated ones with $M_{200} > 10^{15} h^{-1} M_\odot$. This plot demonstrates that, when computed within the whole cluster virial region, there is no relevant dependence upon mass of such fractions. We remind the reader

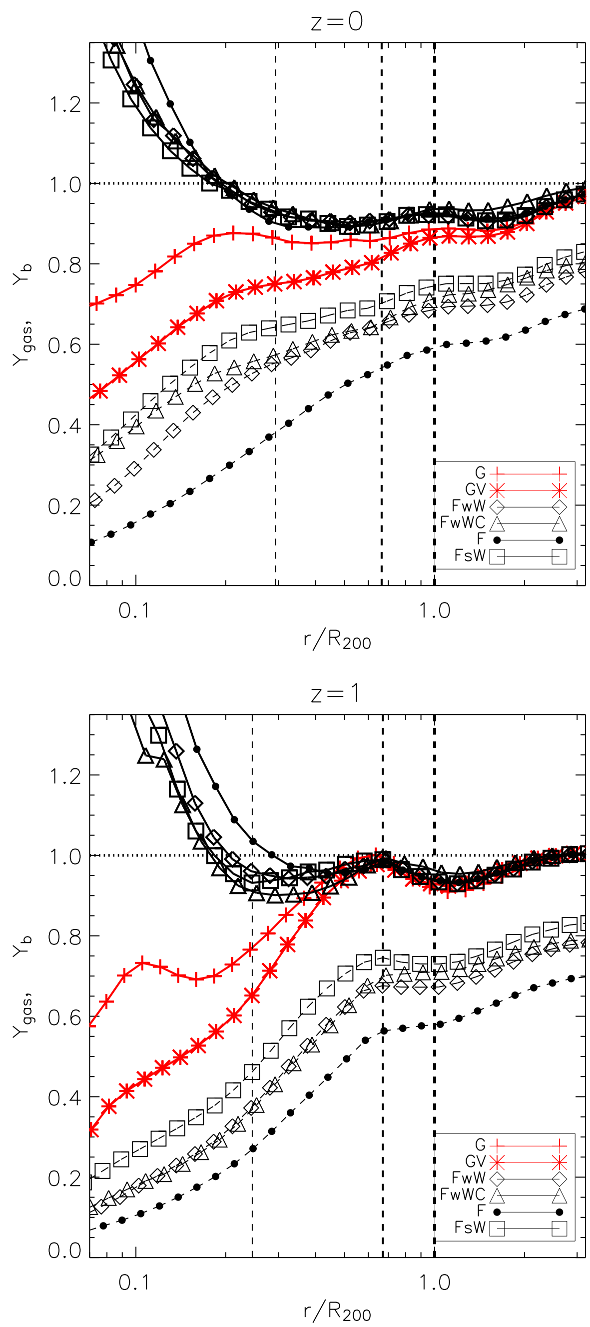

Figure 2. The radial distribution of the gas and baryon mass fractions (in unit of the cosmic baryonic value) at $z = 0$ and 1 for one of the four massive re–simulated systems. The vertical dashed lines indicate the location of R_{2500}, R_{500} and R_{200} for the *Gravitational heating only* case.

that the two sets of clusters have been simulated for the same cosmological model, the only difference being in the value of σ_8, assumed to be 0.8 and 0.9 for the first and for the second set, respectively. In Fig. 1, the re-simulated clusters indicated with a diamond correspond to the same simulation physics as for the clusters extracted from the cosmological box. They show a mean $Y_{\rm b}$ consistent with that measured for the massive systems of the cosmological box, but with a slightly lower value of $Y_{\rm gas}$. This is due to the increase in the cooling efficiency with the amplitude of the

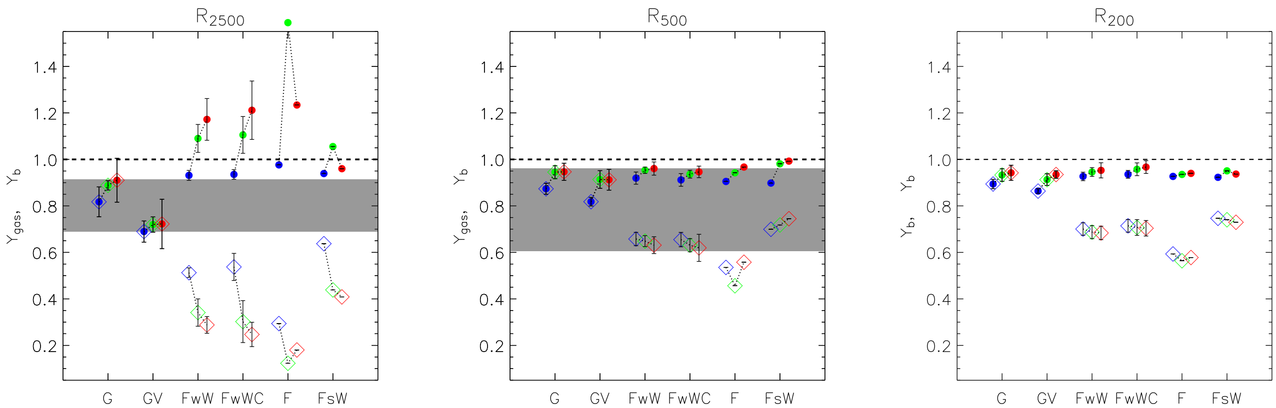

Figure 3. The gas (*diamonds*) and total baryon (*dots*) mass fractions, in unit of the cosmic baryonic value at R_{2500} (left panel), R_{500} (central panel) and R_{200} (right panel). For each physical case considered, we plot the mean and standard deviation values measured at $z = 0$, 0.7 and 1. The shaded region show the error-weighted mean and standard deviation of (1) $f_{\rm gas}(R_{2500})$ estimated from 26 X-ray luminous galaxy clusters in Allen et al. (2004, quoted in Table 2 for a LCDM universe), (2) $f_{\rm gas}(R_{500})$ from 35 highly luminous ($L_{\rm X} \gtrsim 10^{45}$ erg s^{-1}) objects in Ettori & Fabian (1999). The observational data are normalized to $\Omega_{\rm b} h^2 = 0.0214 \pm 0.0020$ (Kirkman et al. 2003), $H_0 = 70$ km s^{-1} Mpc^{-1} and $\Omega_{\rm m} = 0.3$.

power–spectrum, which produces more evolved clusters (Borgani et al. 2005, in preparation).

The radial distribution of the gas and baryon mass fractions in these massive systems present quite a similar behavior. For one representative object, we plot in Fig. 2 these ratios as a function of radius, out to $3 \times R_{200}$, at $z = 0$ and 1, for the six physical schemes adopted in our analysis. The total baryon fraction measured in the radiative models is higher than the value obtained for the non–radiative runs (code= G, GV) within the virial radius and reaches the cosmic value at about $3 \times R_{200}$. The gas fraction is larger when the winds are stronger as a consequence of their effect in preventing gas removal from the hot phase. At $z = 0$, it increases typically with radius reaching 50 and 80 per cent of the value measured at R_{200} at $r \lesssim 0.1 R_{200}$ and at $\sim 0.3 R_{200}$, respectively. At $z = 1$, the gas fraction is less concentrated: the radii at which the 50 and 80 per cent of $f_{\rm gas}(< R_{200})$ is reached are a factor 1.4 and 2 larger than at $z = 0$.

The quantities $Y_{\rm gas}$ and $Y_{\rm b}$ at R_{2500}, R_{500} and R_{200}, as a function of redshift and physics included in the simulations, are plotted in Fig. 3. In the inner cluster regions, the dissipative action of radiative cooling enhances the average $Y_{\rm b}$ to super-cosmic values at high redshift. At late times cooling is less efficient, and $Y_{\rm b}$ declines, although to values (~ 0.9 at $z = 0$) that remain higher than those of the non-radiative runs. A smaller scatter and more widespread agreement among the different physical regimes are instead found in the outskirts ($r \gtrsim R_{500}$). The gas fraction within R_{2500} is about 0.3 times the cosmic value at $z = 1$ and 0.6 at $z = 0$, whereas is more tightly distributed around $0.6-0.7$ at larger radii, with evidence of larger values in the presence of strong winds. We also compare in Fig. 3 our simulation results with the observed $f_{\rm gas}$ distribution in highly X-ray luminous clusters at R_{2500} (from Allen et al. 2004) and at R_{500} (from Ettori & Fabian 1999). Simulations clearly indicate a sizeable underestimate of the hot baryons budget, both at R_{2500} and at R_{500}. When extra physics is added to the action of gravitational heating, lower hot gas fractions result. The discrepancy with the inferred observed fraction signals the existence of systematic errors, either in our physical treatment, or in estimates of the observed fraction, or possibly both. It is worth noticing that total mass estimates, for instance, suffer from systematic differences when measured from X-ray analysis and from dark matter particles in simulations, mainly owing to bias in the X-ray spectral temperature measurements (see, e.g., Mazzotta et al. 2004, Vikhlinin 2005 and, specifically related to the systematics in X-ray mass estimates, Rasia et al. 2005). The observed gas fraction measurements are well represented by the values measured in the non–radiative simulations also in the inner regions, where variations by $\lesssim 15$ per cent due to the action of non-thermal pressure support (induced by the reduced viscosity scheme) encompass the observed variance.

The values of, and the relation between, $Y_{\rm gas}$ and $Y_{\rm star}$ are shown in Fig. 4 and 5. At R_{2500}, the estimate of $Y_{\rm b}$ is strongly affected by the physics involved in the accumulation of the cluster baryons, with super-cosmic values mainly due to a very high star-formation efficiency ($Y_{\rm star} > 0.5$), particularly at high redshift (see Fig. 4). The effect of this cooling excess is to sink more gas in the core to maintain the pressure support, thus making the overall baryon fraction super-cosmic and the gas fraction less concentrated at high redshift. At R_{500} and R_{200}, the dispersion in the estimate of $Y_{\rm b}$ is 2-3 per cent of the measured mean (Fig. 3). We explain the reduction in the scatter at large radii by the common history that the baryons experience in our simulations when the properties are averaged over a volume large enough not to be dominated from the physics of the core. With respect to the mean values measured at R_{2500}, $Y_{\rm star}$ decreases by a factor $\gtrsim 2$ and $Y_{\rm gas}$ increases by more than 30 per cent, with peaks of 2-3 when no winds, or weak winds combined with the effect of conduction, affect the ICM physics (Fig. 5). The ratio $f_{\rm gas}/f_{\rm star}$, that is $\lesssim 1$ at R_{2500} and $z \gtrsim 0.3$, increases with both radius and redshift and becomes $\simeq 3$ at R_{200} and $z = 0$ in the presence of winds (see Fig. 5). Once again, the absence of galactic winds increases the efficiency of star formation and leaves the $f_{\rm gas}/f_{\rm star}$ ratio below 2 within the virial radius. These values are well above the observed constraints, also plotted in Fig. 5. Lin, Mohr & Stanford (2003) compare the gas mass measured in nearby X-ray bright galaxy clusters with the stellar masses evaluated from K-band luminosities of the member galaxies. From their estimates, converted to the total mass measurements in Arnaud et al. (2005), we infer an average $M_{\rm gas}/M_{\rm star} \approx 8.7$ (r.m.s. $= 2.7$) at R_{500} in systems with gas temperatures larger than 3 keV,

that is still a factor between 2.5 and 6 larger than what obtained in our simulated objects (Fig. 5), thus witnessing the presence of significant overcooling.

4 COMPARISON TO PREVIOUS ANALYSES

While the comparison between results from different non–radiative simulations is relatively straightforward, when extra-physics is included, such as radiative cooling, star formation and stellar feedback, the results on the hot and cool baryons distributions is sensitive to the implemented scheme. Therefore, this difference has to be taken into account in performing such a comparison.

In their non–radiative simulations, Eke, Navarro & Frenk (1998) found that the gas fraction within $R_{\rm vir}$ is, on average, 87 per cent of the cosmic value, that is reached at about $3R_{\rm vir}$. For dynamically relaxed systems, they measure $Y_{\rm gas} = 0.824 \pm 0.033$ at $r = 0.25R_{\rm vir} \approx R_{2500}$ (as quoted in Allen et al. 2004). No evident evolution is present between $z = 1$ and 0. A comparable value was obtained as average of the baryon fraction measured in a set of non–radiative simulations of one single cluster presented in the Santa Barbara Comparison Project (Frenk et al. 1999), with $f_{\rm b}/(\Omega_{\rm b}/\Omega_{\rm m})$ of 0.92 (rms: 0.07) at the virial radius. Similar results have been obtained also in other SPH simulations (e.g. Bialek et al. 2001, Muanwong et al. 2002).

These results agree with our estimates for our simulations of massive galaxy clusters with gravitational heating only: $Y_{\rm b}(< R_{200}) = 0.89 \pm 0.02$ (0.90 ± 0.03 at $R_{\rm vir}$). A slight increase at high redshift is however measured ($Y_{\rm b} = 0.94 \pm 0.03$ at $z = 1$). On the contrary, the baryon fraction decreases moving inwards, with $Y_{\rm b}(< R_{500}) = 0.87$ and $Y_{\rm b}(< R_{2500}) = 0.82$

Kravtsov, Nagai & Vikhlinin (2005) studied the baryon fraction in nine galaxy clusters spanning a decade in mass and simulated with the Eulerian adaptive mesh refinement N-body+gasdynamics ART code, for both non–radiative and radiative cases. For non–radiative simulations, they measure $Y_{\rm b} \approx 1$ (at $r \gtrsim 3R_{\rm vir}$), 0.97 ± 0.03 (at $R_{\rm vir}$), 0.94 ± 0.03 (at R_{500}) and 0.85 ± 0.08 (at R_{2500}), that are consistently higher than our values by few per cent. This systematic difference by $\approx 5\%$ at $r \gtrsim R_{2500}$ has been already shown by the comparison between the ART and GADGET codes discussed in Kravtsov et al. (2005) and, even though smaller than the 10% differences measured in the Santa Barbara cluster comparison project (Frenk et al. 1999) between the gas fraction obtained from Eulerian and SPH codes, is still relevant when using simulations to calibrate systematics in the estimate of the baryon fraction in clusters.

When the radiative cooling and other physical processes are turned on, the number of reliable comparisons that can be done is reduced. In the radiative simulations of Muanwong et al. (2002), $Y_{\rm gas}$ is between $0.6 - 0.7$ in high$-M$ systems and $Y_{\rm b} \approx 0.9$ at the virial radius. When pre–heating with an extra energy of 1.5 keV per particle at $z = 4$, these authors find $Y_{\rm gas} \sim Y_{\rm b} \approx 0.8 - 0.9$. Kravtsov et al. (2005) measure the gas fraction to rise from 0.46 ± 0.06 (at R_{2500}) to 0.65 ± 0.06 (at $R_{\rm vir}$), whereas $Y_{\rm b}$ remains always around 1 (from 1.22 ± 0.11 at R_{2500} to 1.02 ± 0.02 at $R_{\rm vir}$). These values are roughly in agreement with our results, in particular for the set of simulated objects with weak winds: at $z = 0$, $Y_{\rm gas} = 0.51 \pm 0.02$ at R_{2500} and 0.70 ± 0.03 at R_{200}, while $Y_{\rm b}$ is flat around 0.93 ± 0.02 and never super-cosmic, i.e. $Y_{\rm b} < 1$. Different numerical implementations of the cooling, star–formation and feedback processes are expected to contribute to this systematic difference between the predictions of ART and GADGET simulations. These differences are, in fact, more significant in the radiative runs and depend on the amount of baryons cooled in stars (see also Kravtsov et al. 2005). Such differences, which are numerical in origin, should definitely be considered as theoretical uncertainties, when using simulations to calibrate systematic biases in the observational estimate of the baryon fraction within clusters. The action of stronger winds is to increase the gas fraction, whereas the absence of winds reduces $Y_{\rm gas}$ to 0.29 and 0.59 at R_{2500} and R_{200}, respectively.

5 IMPLICATIONS FOR THE CONSTRAINTS ON COSMOLOGICAL PARAMETERS

Our results have a direct implication on the systematics that affect the constraints on the cosmological parameters obtained through the cluster baryon mass fraction (e.g. White et al. 1993, Evrard 1997, Allen et al. 2002, Ettori et al. 2003, Ettori 2003, Allen et al. 2004). We remind that, once a representative gas fraction, denoted here $\hat{f}_{\rm gas}$, is directly measured from X-ray observations and a statistical relation between the average $\hat{f}_{\rm star}$ and $\hat{f}_{\rm gas}$ is adopted, the cosmic mass density parameter can be then evaluated as

$$\Omega_{\rm m} = \frac{Y_{\rm b}\ \Omega_{\rm b}}{\hat{f}_{\rm gas}\left(1 + \hat{f}_{\rm star}/\hat{f}_{\rm gas}\right)}, \tag{1}$$

where the “hat” indicates the observed quantities and the cosmic baryon density $\Omega_{\rm b}$ is assumed from primordial nucleosynthesis calculations or the measured anisotropies in the cosmic microwave background. In recent years this method has been also extended to the measure of the dark energy density parameter, (Ω_Λ, w; see, e.g., Allen et al. 2002, Ettori et al. 2003, Allen et al. 2004) under the assumption that the gas fraction remains constant in redshift (Sasaki 1996, Pen 1997). Since the gas fraction scales with the angular diameter distance as $f_{\rm gas} \propto d_{\rm A}^{1.5}$, the best choice of cosmological parameters is defined as the set of values that minimizes the χ^2 distribution of the measured gas fraction at different redshifts with respect to the reference value:

$$f_{\rm gas}^{\Lambda CDM} = \frac{Y_{\rm b}\ \Omega_{\rm b}\Omega_{\rm m}^{-1}}{\left(1 + \hat{f}_{\rm star}/\hat{f}_{\rm gas}\right)} \left[\frac{d_{\rm A}(z; \Omega_{\rm m} = 0.3; \Omega_\Lambda = 0.7)}{d_{\rm A}(z; \Omega_{\rm m}; \Omega_\Lambda)}\right]^{1.5}. \tag{2}$$

Despite its conceptual simplicity and straightforward application, this method makes some assumptions that have to be tested before the error bars estimated for the matter and dark–energy density parameters can be accepted as robust and reliable determination of both statistical and systematic uncertainties. In the present discussion, we highlight two of the assumptions generally adopted, but never verified: (1) the mean value of $Y_{\rm b}$ does not evolve with redshift, (2) a fixed ratio between $f_{\rm star}$ and $f_{\rm gas}$ holds in a cluster at any radius and redshift. As we have shown here, both these assumptions are not valid in our simulated dataset whatever is the physics included in the simulations, in particular when considering the inner part of the clusters. Allen et al. (2004) use the simulation results by Eke et al. (1998) to fix $Y_{\rm b} = 0.824 \pm 0.033$ at $r \approx R_{2500}$ for their sample of *Chandra* exposures of the largest relaxed clusters with redshift between 0.07 and 0.9. We notice, for instance, that, while this value is in agreement with our simulation results at $z = 0$ in the runs with *Gravitational heating only* ($Y_{\rm b} = 0.82 \pm 0.06$), it is definitely lower than what we estimate at higher redshift (e.g. $Y_{\rm b} = 0.86, 0.89, 0.91$ at $z = 0.3, 0.7, 1$, respectively). This increase of $Y_{\rm b}$ with redshift is the consequence of the different accretion pattern of shock-heated baryons at different epochs. At later times, accreting gas had more time to be pre-

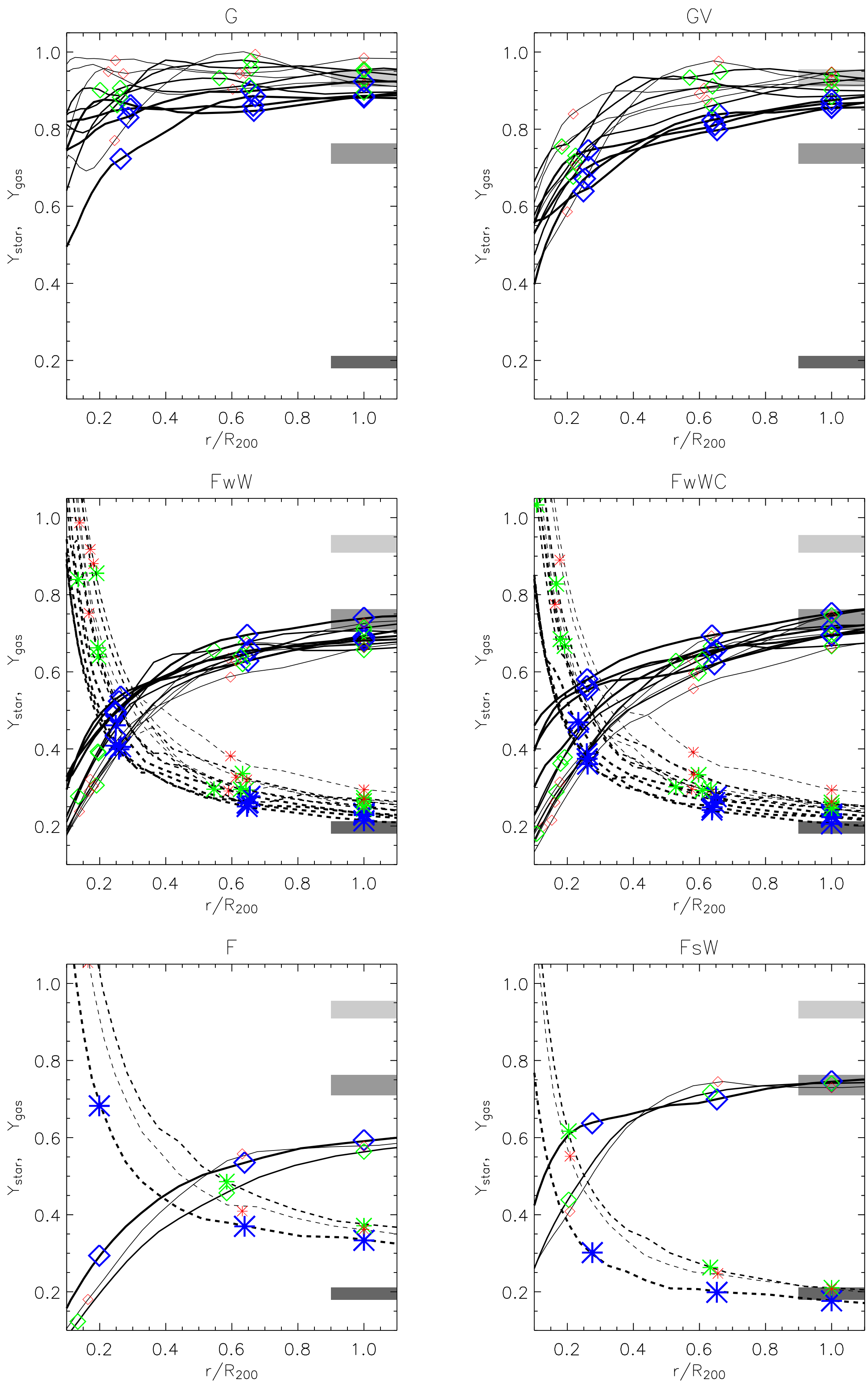

Figure 4. The comparison between the outputs of the 6 different physical schemes investigated. The gas (*solid line*) and stellar (*dashed line*) mass fractions, normalized to the cosmic value, are plotted at $R_{2500} (\approx 0.3 R_{200})$, $R_{500} (\approx 0.7 R_{200})$ and R_{200}. Their evolution with redshift is indicated by the thickness of the lines (from thickest line/larger symbols to thinnest line/smaller symbols: z = 0, 0.7, 1). The shaded regions indicate the 1σ range of $Y_{\rm star}$, $Y_{\rm gas}$ and

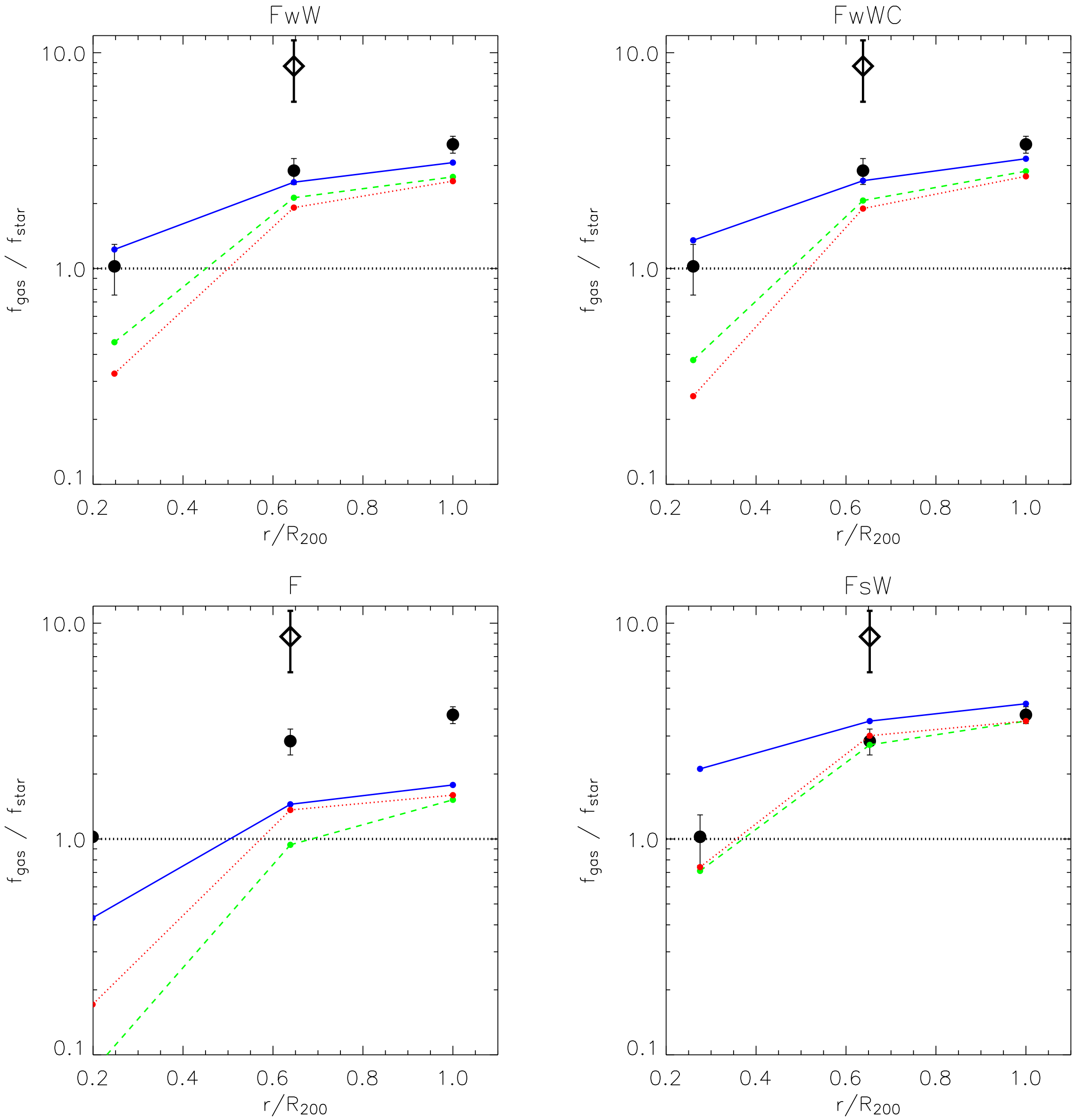

Figure 5. Ratios between the cumulative gas and stellar mass fractions within a given radius as a function redshift (*solid line*: $z = 0$; *dashed line*: $z = 0.7$; *dotted line*: $z = 1$) for the different physics included in the simulations. The large dots show the mean value (and relative standard deviation) obtained from the cosmological sample. The diamonds indicate the ratios expected, for a given M_{500}, from the equation 10 of Lin, Mohr & Stanford (2003), based on near–infrared observations of massive X-ray galaxy clusters.

shocked into filaments. As a consequence, they have a relatively higher entropy, thus relatively increasing the radius (in unit of the virial radius) where accretion shocks take place. This is the reason why, as shown in Fig. 2, at $z = 1$ $f_{\rm b}$ reaches the cosmic value at relatevely smaller radii than at $z = 0$.

Since the tighter cosmological constraints provided by the cluster gas fraction alone are on $\Omega_{\rm m}$ (of the order of 16 per cent at 1σ level; e.g. Allen et al. 2004), we try to quantify the effect of the variation of the baryonic components with the radius and the redshift on this estimate. To this purpose, we use equation 1 and evaluate first how $\Omega_{\rm m}$ changes by varying $Y_{\rm b}$. In runs with gravitational heating only, the increasing baryon fraction with redshift induces larger estimate of $\Omega_{\rm m}$ with respect to what obtained from local measurements of $Y_{\rm b}$:

$$\frac{\Omega'_{\rm m} - \Omega_{\rm m}}{\Omega_{\rm m}} = \frac{\Delta\Omega_{\rm m}}{\Omega_{\rm m}} = \frac{Y_{\rm b}(< R_\Delta, z = z_o)}{Y_{\rm b}(< R_\Delta, z = 0)} - 1 \qquad (3)$$

is $+0.09$ at $R_\Delta = R_{2500}$ and $z_o = 0.7$ for the case with gravitational heating only and $+0.11$ at $z_o = 1$. (Here the prime symbol $'$ indicates the corrected value with respect to the reference one). Using instead the runs with reduced viscosity, the deviation decreases to about $+0.05$. As for the radiative runs, the bias is of the order of 20 per cent, that reduces to 2 per cent in presence of strong winds at $z = 1$. When outer cluster regions are mapped (i.e. $r \sim R_{500}$), the deviation converges to similar amounts due to the limited impact of cooling and feedback over large volumes: variations between $+0.03$ (weak winds) and $+0.10$ (strong winds) become comparable to $\Delta\Omega_{\rm m}/\Omega_{\rm m} \approx +0.08$ as measured in non–radiative runs.

A further contribution to the uncertainties comes from the dependence upon the radius and redshift of the ratio $f_{\rm star}/f_{\rm gas}$. In the observational determination of the baryon fraction from eqn. 1, this quantity is generally assumed to be 0.16, as measured in the Coma cluster within the virial radius [e.g. White et al. 1993; note that our estimate from Lin et al. (2003) and adopting the total mass measurements in Arnaud et al. (2005) is 0.11 ± 0.04]. If we compare the ratio $\phi = f_{\rm star}/f_{\rm gas}$ measured for a Coma–like simulated cluster at R_{200} and $z = 0$ with the estimates at other redshifts ($z_o = 0.7$ and 1; see, e.g., Fig. 5), we evaluate from equation 1

$$\frac{\Omega_{\rm m}' - \Omega_{\rm m}}{\Omega_{\rm m}} = \frac{\Delta\Omega_{\rm m}}{\Omega_{\rm m}} = \frac{1+\phi(< R_\Delta, z=0)}{1+\phi(< R_\Delta, z=z_o)} - 1 \approx -0.05 \,. \quad (4)$$

When $\phi = f_{\rm star}/f_{\rm gas}$ measured locally at R_{2500} is compared with the corresponding value at different redshifts, the deviation ranges between -0.74 (when winds are excluded) and -0.38 (when strong winds are present), whereas it is about -0.10 at R_{500}.

As for the runs with gravitational heating only the effect of the variation of $Y_{\rm b}$ with redshift and overdensity implies $\Delta\Omega_{\rm m}/\Omega_{\rm m} \lesssim +0.11$, thus comparable to the current statistical uncertainties from *Chandra* observations of the massive clusters out to $z = 1.3$ (Ettori et al. 2003, Allen et al. 2004). However, when the extra-physics of the radiative runs is included, $\Delta\Omega_{\rm m}/\Omega_{\rm m}$ has two contributions of $\approx +0.10$ and $\lesssim -0.05$, due to an increase with redshift of (1) $Y_{\rm b}$ (see Fig. 3) and (2) the stellar to gas mass fraction ratio (see Fig. 5). Both these effects are caused by a more efficient star formation in high redshift clusters.

In general, our results indicate that it may be dangerous to use simulations to calibrate observational biases for precision determination of cosmological parameters from the gas fraction in clusters. Although none of our simulation models includes a fair description of the actual ICM physics, it is interesting that different models provide different redshift–dependent corrections for the estimate of the cosmic baryon fraction from observations of the gas and star density distribution within clusters. If applied to observational data, such corrections would induce sizeable differences in the determination of the matter and dark energy density parameters.

6 SUMMARY AND DISCUSSION

We have analyzed the distribution of gas and stellar mass fraction in simulated massive X-ray galaxy clusters as function of (i) the radius expressed in the form of R_{2500}, R_{500} and R_{200}, (ii) the redshift at which the structure is identified, (iii) the physical processes determining the evolution of the baryons in the cluster potential wells (i.e. gravitational heating, radiative cooling, star formation, conduction and galactic winds powered by supernova explosions).

Our main results can be summarized as follows.

(i). As for the cluster set extracted from a cosmological box, which are simulated by including cooling, star formation and feedback with weak (340 km s^{-1}) winds, we find at R_{200} $Y_{\rm b} = 0.93$, $Y_{\rm gas} = 0.74$ and $Y_{\rm star} = 0.20$, with scatter around these values of 2, 4 and 8 per cent, respectively. These results are virtually independent of the cluster mass over the range $M_{\rm vir} \approx (0.5 - 13) \times 10^{14} h^{-1} M_\odot$. The dispersion relative to the mean value measured at R_{2500} is a factor of about 3 larger than R_{200}.

(ii). In the four massive ($M_{200} > 10^{15} h^{-1} M_\odot$) galaxy clusters simulated with 6 different physical schemes, we find that the cosmic value of the baryon fraction $\Omega_{\rm b}/\Omega_{\rm m}$ is reached at about $3 \times R_{200}$. The gas fraction increases radially, reaching 50 (80) per cent of the value measured at R_{200} at $r \approx 0.1(0.3) R_{200}$ at $z = 0$. At $z = 1$ the same values are reached at radii which are about 40 per cent larger. This indicates that $f_{\rm gas}$ tends to be less concentrated at higher redshift, where the more efficient star formation causes a more efficient removal of gas from the hot phase in the central cluster regions. We also find that in these clusters the amount of hot baryons, in unit of the cosmic value, is less scattered and less dependent on the particular physics adopted when it is measured over larger cluster regions. In the runs with *Gravitational heating only*, $Y_{\rm b} = f_{\rm bar}/(\Omega_{\rm b}/\Omega_{\rm m})$ ranges between 0.82 ± 0.06 (at R_{2500}) and 0.89 ± 0.02 (at R_{200}) at $z = 0$. It increases at $z = 1$ to 0.91 ± 0.10, 0.95 ± 0.04 and 0.94 ± 0.03 at R_{2500}, R_{500} and R_{200}, respectively. This increase of $Y_{\rm b}$ with z owes to the smaller radii (in units of the virial radius) at higher redshift where shock-heated baryons accrete, permitting the $f_{\rm b}$ values to reach the cosmic value at higher overdensities, for example, at $z = 1$ than at $z = 0$ (see, e.g., Fig. 2). These values are roughly in agreement with observational constraints obtained from highly X-ray luminous clusters (e.g. Ettori & Fabian 1999, Allen et al. 2004) at R_{2500} and R_{500}. Using an SPH scheme with reduced viscosity, the non–thermal pressure support contributed by turbulent gas motions, reduces the gas fraction by 15 per cent at R_{2500} and by $\sim$5 per cent at $r > R_{500}$.

Adding extra-physics to the action of gravity reduces the amount of diffuse baryons by 20–40 (20–65) per cent at R_{500} (R_{2500}). This is due to the high star formation efficiency that is not sufficiently mitigated by our assumed supernova feedback. The presence of strong winds (assumed here $v \lesssim 480$ km s^{-1}) induces the following effects: (1) a reduction of $Y_{\rm star}$ by about a factor of 2 with respect to the case with no winds; (2) a milder radial dependence of $Y_{\rm star}$ and $Y_{\rm gas}$; (3) larger values for the ratio between $f_{\rm gas}$ and $f_{\rm star}$, that is however still smaller, by about a factor 2.5, than the observed values (Lin et al. 2003) .

(iii). At R_{2500}, the estimate of $Y_{\rm b}$ is strongly affected by the physics included in the simulations. Super-cosmic values are found for the radiative runs, as a consequence of the exceedingly efficient cooling process, which causes a rapid sinking of baryons in the cluster cores. Moreover, differences in the formation history of individual clusters contribute to a wider spread in the $Y_{\rm b}$ values, as shown in the runs including only gravitational heating. In these cases, the standard deviation is of about 10 per cent.

(iv). At R_{500} and R_{200}, the dispersion in the estimate of $Y_{\rm b}$ is 2-3% of the measured mean. With respect to the mean values measured at R_{2500}, $Y_{\rm star}$ decreases by a factor $\gtrsim 2$ and $Y_{\rm gas}$ increases by more than 1.3, with peaks of 2-3 in the simulations without winds, or with weak winds combined with conduction at $1/3$ the Spitzer value.

We explain the reduction in the scatter at $r > R_{500}$ by the common history that the baryons experience when their properties are averaged over a large enough volume. In the outer regions, the gas evolution is mainly driven by the action of gravity. The ratio $f_{\rm gas}/f_{\rm star}$, that is $\lesssim 1$ at R_{2500} and $z \gtrsim 0.3$, increases with radius and redshift and becomes $\simeq 3$ at R_{200} and $z = 0$ in the presence of winds.

(v). Our results have direct implications on the calibration of the systematic effects that limit the use of the X-ray gas mass fraction as a cosmological tool (e.g. Evrard 1997, Ettori et al. 2003, Allen et al. 2004). Owing to the uncertainties in the modelization of the ICM, we emphasize that our simulations cannot be used to calibrate the observed $f_{\rm gas}$. However, our results emphasize the potential problems related to the estimate of the cosmic baryon fraction from the gas mass fraction as measured in central cluster regions; i.e. the variation of $Y_{\rm b}$ with redshift and a proper estimate of the

contribution of stars in galaxies to the total cluster baryon budget as a function of radius and redshift.

For the non–radiative runs the effect of the variation of Y_b with redshift and overdensity implies a $\Delta\Omega_\mathrm{m}/\Omega_\mathrm{m} \lesssim +0.11$ that is comparable to the typical statistical uncertainties from *Chandra* observations of the massive clusters out to redshift $z = 1.3$ (Ettori et al. 2003, Allen et al. 2004). However, when star formation and feedback are also included, $\Delta\Omega_\mathrm{m}/\Omega_\mathrm{m}$ has two contributions of $\approx +0.10$ and $\lesssim -0.05$, due to an increase with redshift of (1) Y_b (see Fig. 3) and (2) ration between stellar and gas mass (see Fig. 5).

Our results show that star formation in our radiative runs is still too efficient, especially in the cluster central regions, even in the presence of rather strong galactic winds. As a result, the impact of cooling and star formation in the simulated clusters is still much larger than in realistic cases. On the one hand, this calls for the need to introduce more effective feedback mechanisms, e.g. related to Active Galactic Nuclei, which are able to prevent overcooling in the central cluster regions (see, e.g., the effect of the injection of supersonic AGN jets in the ICM of simulated clusters in Zanni et al. 2005). On the other hand, our analysis demonstrates that using simulations to calibrate the systematic uncertainties in the estimate of cosmological parameters from the cluster gas mass fraction may be quite problematic, especially if it has to be used as a high–precision tool to measure the cosmic density parameters associated to matter and dark energy.

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Table 1. Distribution of the baryons in the two sets of simulated galaxy clusters. The mean values of the indicated ratios are shown.

STATUS	N	z	R_{2500}			R_{500}			R_{200}		
			$Y_{\rm gas}$	$Y_{\rm star}$	$Y_{\rm b}$	$Y_{\rm gas}$	$Y_{\rm star}$	$Y_{\rm b}$	$Y_{\rm gas}$	$Y_{\rm star}$	$Y_{\rm b}$
G	4	0.0	0.817(0.064)	–	0.817(0.064)	0.874(0.023)	–	0.874(0.023)	0.894(0.020)	–	0.894(0.020)
...		0.3	0.864(0.057)	–	0.864(0.057)	0.907(0.022)	–	0.907(0.022)	0.926(0.019)	–	0.926(0.019)
...		0.7	0.888(0.020)	–	0.888(0.020)	0.945(0.028)	–	0.945(0.028)	0.933(0.027)	–	0.933(0.027)
...		1.0	0.910(0.094)	–	0.910(0.094)	0.947(0.037)	–	0.947(0.037)	0.942(0.033)	–	0.942(0.033)
GV	4	0.0	0.690(0.045)	–	0.690(0.045)	0.818(0.018)	–	0.818(0.018)	0.864(0.010)	–	0.864(0.010)
...		0.3	0.720(0.069)	–	0.720(0.069)	0.865(0.019)	–	0.865(0.019)	0.900(0.013)	–	0.900(0.013)
...		0.7	0.720(0.033)	–	0.720(0.033)	0.914(0.038)	–	0.914(0.038)	0.913(0.025)	–	0.913(0.025)
...		1.0	0.722(0.106)	–	0.722(0.106)	0.912(0.045)	–	0.912(0.045)	0.935(0.016)	–	0.935(0.016)
FwW	4	0.0	0.513(0.021)	0.419(0.029)	0.931(0.021)	0.658(0.029)	0.262(0.011)	0.920(0.026)	0.701(0.027)	0.226(0.009)	0.927(0.018)
...		0.3	0.448(0.040)	0.565(0.054)	1.013(0.063)	0.664(0.025)	0.286(0.022)	0.950(0.027)	0.708(0.018)	0.243(0.018)	0.951(0.019)
...		0.7	0.341(0.059)	0.749(0.114)	1.090(0.060)	0.649(0.024)	0.305(0.021)	0.953(0.014)	0.687(0.028)	0.259(0.013)	0.946(0.019)
...		1.0	0.288(0.036)	0.884(0.098)	1.172(0.090)	0.631(0.036)	0.330(0.038)	0.961(0.028)	0.684(0.029)	0.269(0.019)	0.953(0.033)
FwWC	4	0.0	0.538(0.058)	0.398(0.049)	0.935(0.021)	0.655(0.031)	0.257(0.015)	0.912(0.027)	0.714(0.027)	0.221(0.011)	0.936(0.017)
...		0.3	0.448(0.070)	0.552(0.072)	1.000(0.063)	0.652(0.026)	0.281(0.017)	0.932(0.025)	0.726(0.026)	0.236(0.017)	0.962(0.014)
...		0.7	0.302(0.090)	0.803(0.169)	1.105(0.079)	0.631(0.028)	0.306(0.018)	0.937(0.017)	0.707(0.034)	0.250(0.008)	0.958(0.027)
...		1.0	0.247(0.052)	0.965(0.160)	1.212(0.126)	0.620(0.058)	0.327(0.048)	0.946(0.025)	0.704(0.033)	0.263(0.021)	0.967(0.027)
F	1	0.0	0.294(–)	0.682(–)	0.976(–)	0.535(–)	0.370(–)	0.905(–)	0.593(–)	0.333(–)	0.927(–)
...		0.3	0.169(–)	1.083(–)	1.252(–)	0.491(–)	0.447(–)	0.938(–)	0.594(–)	0.369(–)	0.963(–)
...		0.7	0.123(–)	1.465(–)	1.588(–)	0.456(–)	0.486(–)	0.942(–)	0.564(–)	0.371(–)	0.935(–)
...		1.0	0.180(–)	1.054(–)	1.234(–)	0.558(–)	0.409(–)	0.967(–)	0.578(–)	0.362(–)	0.940(–)
FsW	1	0.0	0.638(–)	0.302(–)	0.939(–)	0.699(–)	0.199(–)	0.898(–)	0.747(–)	0.176(–)	0.923(–)
...		0.3	0.600(–)	0.439(–)	1.038(–)	0.731(–)	0.245(–)	0.976(–)	0.774(–)	0.203(–)	0.978(–)
...		0.7	0.439(–)	0.617(–)	1.055(–)	0.718(–)	0.263(–)	0.981(–)	0.740(–)	0.210(–)	0.951(–)
...		1.0	0.409(–)	0.552(–)	0.960(–)	0.745(–)	0.248(–)	0.993(–)	0.730(–)	0.207(–)	0.937(–)